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DAMAGE AND FRACTURE OF A WELDED TRUSS WITH PARALLEL BELTS UNDER CYCLIC LOADS

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Abstract. *The paper determines the effect of operational cyclic loads on damage to welded trusses. A physical model of a 600x120 rectangular welded truss with parallel belts was developed for the study. The scheme of its basing and loading corresponds to the conditions for a real 12000x2400 truss. The physical model of a 600x120 truss was investigated under static and cyclic loads on the STM-100 test complex. Under cyclic loads, the fatigue crack nucleation site was identified, its propagation rate was determined, and the critical crack length at which the truss collapses was found. An analytical dependence has been developed to determine the dynamics of fatigue crack propagation during the operation of a truss under cyclic loads. Recommendations for the safe operation of a welded truss under cyclic loads, its strengthening and repair to increase the service life of the structure are formulated. Using the results of the work in engineering practice will help prevent accidental destruction of the truss during its operation.*

Key words: *welded truss, strength and deformability of the truss, cyclic loads, fracture of the truss.*

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1. INTRODUCTION

The paper deals with the urgent scientific and technical problem of determining the effect of operational cyclic loads on damage to welded trusses. The solution to this problem will make it possible to maximise the load-bearing capacity of the structure and prevent its accidental destruction during operation. According to the terms of reference, it is necessary to identify the location of fatigue crack initiation and the possibility of safe operation of a welded truss with an existing crack before the onset of the limit state of the structure. The truss has a rectangular configuration with dimensions of 12000x2400 mm and is intended to be installed by the support units of the lower belt on the columns and fixed to the units on the upper belt of the crane in the production facility of Smarttechbud LLC.

A bottleneck in the design of welded trusses is their design when subjected to cyclic loads. A significant number of welded truss structures are operated under cyclic loads (cranes, overhead conveyors, bridge structures, power line towers, etc.) It is quite difficult to achieve high accuracy using computational methods. The reason is the multi-parameter influence of design, process, operational and accident factors. The issue of strength and reliability is solved by introducing additional safety factors that increase the material consumption and, consequently, the cost of the truss [1].

Of course, the most complete way to take into account all the parameters of the impact on the structure is to perform a full-scale experiment. However, it is difficult to carry out such an experiment for the study of full-scale welded trusses due to the high cost of prototypes and the need for powerful, and therefore expensive, testing equipment. Therefore, semi-natural studies are often used as an alternative, i.e., not a full-scale truss, but its physical (scale) model is tested.

Among the modern domestic scientists who have been engaged in physical modelling of welded trusses, the works of Shynhera N.Y. [2], Basara M.A. [3, 4] and others are known. The works of foreign researchers [5...15] are also worthy of attention. Such approaches consist in observing the conditions that determine the relationship between the parameters of the model

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and real structures, as well as the rules for converting the studied values from the model to the real structure and vice versa.

The aim of the study is to identify the location of fatigue crack initiation, the dynamics of its propagation during the operation of the truss under cyclic loads, and the possibility of safe operation of a welded truss with an existing crack before the onset of the limit state of the structure.

Setting the task(s).

In order to achieve the research objective, the following tasks need to be solved:

– to develop the design of a physical model of a welded truss and a methodology for conducting semi-natural experimental studies under static and cyclic loads;

– to perform a semi-natural force experiment, to form information arrays based on the results of research and analyse them;

– formulate general conclusions based on the research results and recommendations for their practical use.

2. EXPERIMENTAL METHODS

For the study, according to the terms of reference, we have a rectangular welded truss of 12000x2400 mm (Fig. 1.1).

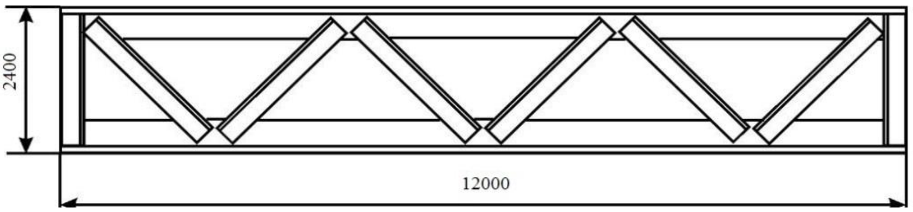


Figure 1. Design of a full-scale truss 12000x2400 mm

All structural elements of the truss (Fig. 1) are made of rolled steel angles 80x80x10 mm. The diagram of the truss base and loading is shown in Fig. 2.

Based on the design of the full-scale farm, a physical model was developed (Fig. 3).

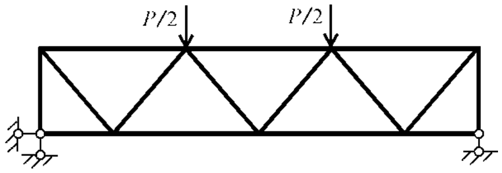


Figure 2. Diagram of the welded truss base and loading

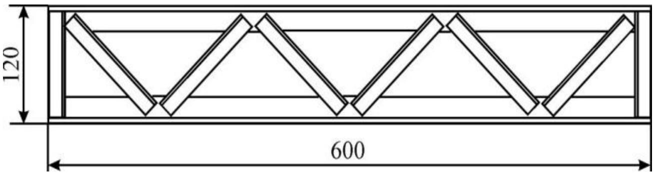
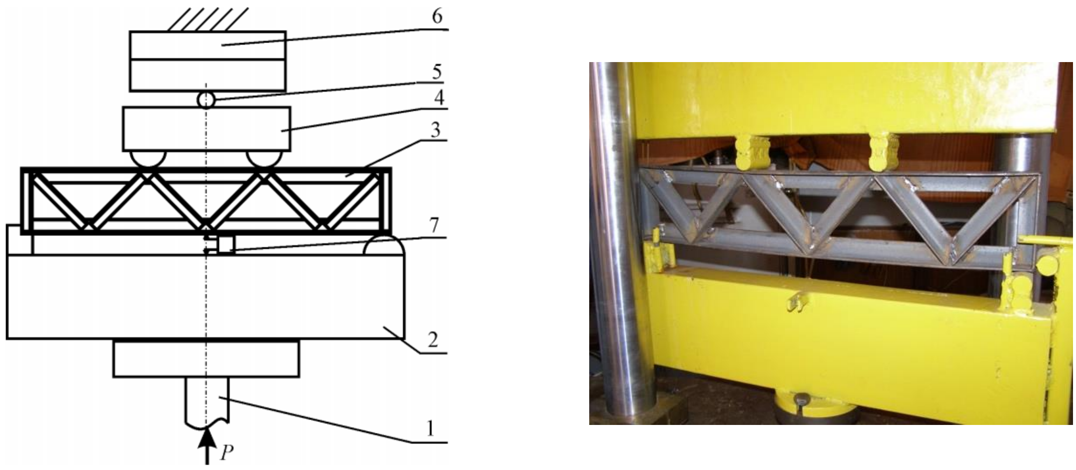


Figure 3. Design of the physical model 600x120 welded truss

All elements of the physical model (Fig. 3) are made of rolled angles 20x20x3 mm of ordinary quality steel VSt3ps. All welds on the samples were made by semi-automatic arc welding with direct current of direct polarity using a 1.2 mm diameter wire electrode Sv-08G2S in CO_2.

A force experiment for the physical model of a 600x120 welded truss according to Fig. 3 to determine the parameters of its deformation and fracture conditions was performed on the electrohydraulic testing complex STM-100.

The scheme of experimental loading of samples on the test complex is shown in Fig. 4. The experimental loads *P* are created by the rod (1) of the hydraulic machine and transferred to the test truss (3) through the stand (2). The traverse (4) receives the load from the two nodes of the truss, balancing it with a cylindrical joint (5) and transferring it to a rigidly fixed dynamometer (6). The dynamometer (6) records the power signal, and the strain gauge (7) records the strain of the sample along the loading line.



a *b*

Figure 4. Implementation of the experimental loading of samples on the test complex STM-100. *a* – structural diagram; *b* – sample 3 in fixture 2, 3

The test facility provides static and cyclic tensile and compressive tests.

The static load test was performed in a soft mode (force control). During the static tests, the load was increased stepwise by 500 N with intermediate visual inspection of the structure and recording of the force, rod displacement, and deflection deformation of the lower girders. Damage to the truss in the form of cracks and bends in the elements was visually monitored. Loading was performed until the structure was destroyed.

During the tests, the STM-100 was controlled by a personal computer. The input parameters were entered in TestBuilder (fatigue tool).

Two samples made according to the developed design for the physical model of a 600x120 mm welded truss were used for full-scale studies (Fig. 3). One specimen was tested under static loading, the other – under cyclic effects.

The experimental specimen was loaded with static forces until it was destroyed (Fig. 5).

3. RESULTS AND DISCUSSION

Based on the results of field tests of one sample under static loads, an experimental information database was obtained. The numerical results of the study are presented in Table 1.

a *b*

Figure 5. Sample of a welded truss on the STM-100 test complex before loading (*a*) and after fracture (*b*)

Table 1

Deformation values of the physical model of a welded truss
under different loads according to the results of a semi-natural experiment

Load P, kN	5	10	15	20	25	30	35	40	45
Deformation δ_{test}, mm	0,21	0,32	0,54	0,71	0,82	1,02	1,27	1,52	2,13

Based on the results of the experiment (Table 1), a deformation diagram of the tested specimens of the physical model of a 600x120 welded truss was constructed (Fig. 6).

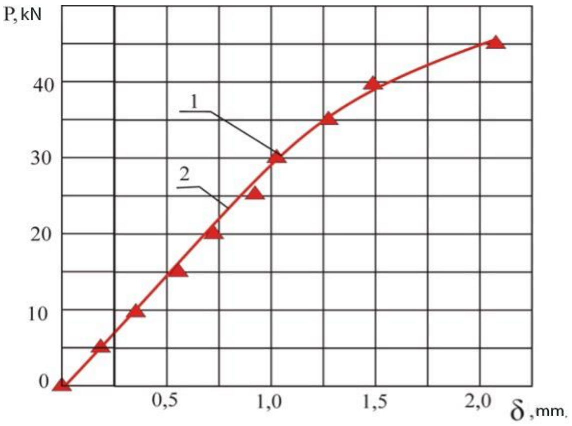


Figure 6. Deformation diagram of the physical model of a 600x120 welded truss based on the results of the experiment: 1 – according to experimental data; 2 – according to the results of linear approximation of experimental data

The diagram shows a linear deformation area at loads up to 30 kN and a plastic deformation area at higher load levels.

To identify the features of damage and fracture of a full-scale welded truss, the test parameters of the physical model under cyclic loads were selected. The choice of modes is determined by the parameters of the operating loads of a full-scale truss.

For cyclic loads, the parameters were taken according to Table 2.

Table 2

Modes of cyclic loading of the physical model of a welded truss

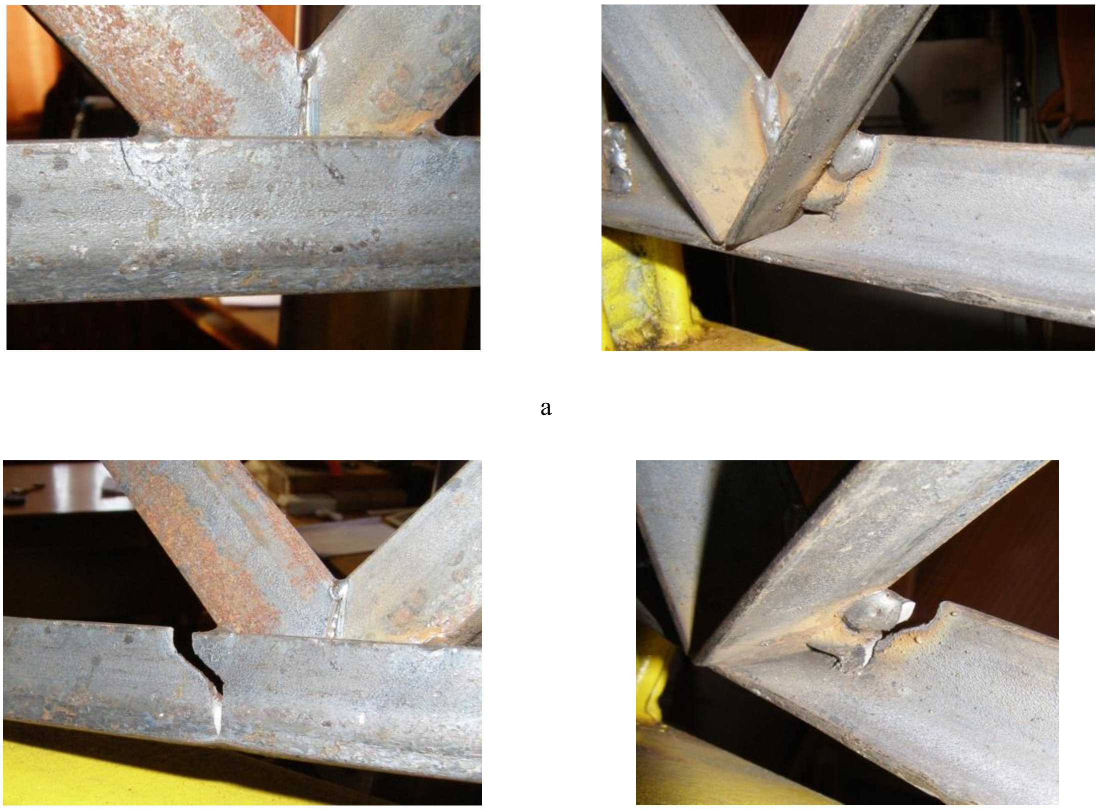
Parameters	Meaning
Average cycle load	$P_m = 15$ kN
Maximum cycle load	$P_{max} = 20$ kN
Minimum cycle load	$P_{min} = 10$ kN
Coefficient of load asymmetry in the cycle	R= $P_{min} / P_{max} = 0.5$;
Cycle load amplitude	$2P_1 = 10$ kN
Load frequency	75 Hz
The shape of the cyclogram	Sine wave

The loads were selected based on the following considerations. The maximum load in a cycle was 2/3 of the static load at the limit of linear deformation. This will make it possible to work under conditions of multi-cycle fatigue and not to make significant safety margins for static loads. In the future, this approach will be convenient for generalising the research results to a full-scale truss.

The frequency for the experiment was increased to reduce the test time.

One sample of a physical model of a 600x120 welded truss was used for full-scale studies under cyclic loads (Fig. 3).

During the cyclic loading, the state of the structure as a whole was visually monitored to identify the location of the initial fatigue crack initiation. When a visually detectable crack appeared (Fig. 7a), its length was measured and the number of cycles n_1 was recorded by the counter of the testing machine.


a

b

Figure 7. Fatigue crack at the initial stage of fatigue damage (a) and at the edge of the limit state of the structure (b)

During the experiment, the length of the crack (l, mm) was recorded after 1x10^5 cycles (n, cycle). The crack was photographed at different stages of its propagation.

The crack size and its dimensions were recorded at the level of the limit state of the structure (Fig. 7b). The numerical results of the study are listed in Table 3.

Table 3

Crack length according to the results of full-scale studies of the physical model of a welded truss under cyclic loading

Number of cycles, n x 10^5	0	1	2	3	4	5	6	7
Crack length l, *mm*	3,8	4,8	5,6	7,2	9,7	13,5	18,9	26,8

After the crack reached a critical size (the vertical wall of the corner was completely damaged), the truss collapsed (Fig. 8).

According to the results of the experiment, it was determined that before the appearance of visually noticeable damage, the number of loading cycles

$$n_1 = 10.9 \text{ x } 10^5 \text{ cycles},$$

and to the loss of firmness afterwards

$$n = 7.2 \text{ x } 10^5 \text{ cycles}.$$

Based on the results of the experiment, a graph of crack propagation during cyclic loading was constructed (Fig. 9).

Figure 8. Physical model after fatigue failure

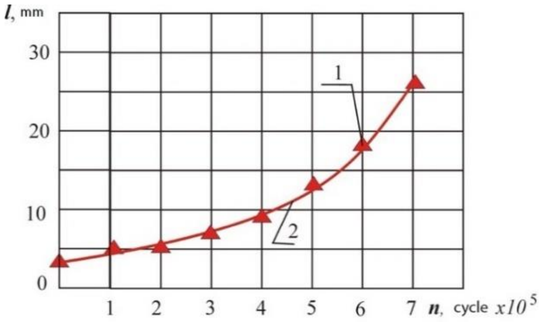


Figure 9. Crack propagation dynamics during cyclic loading

In the graph, point 1 was obtained from the results of the numerical experimental base (Table 3), line 2 was obtained by linear approximation of the experimental points.

For the practical use of the results of the work and determination of the performance of the truss, an analytical dependence was developed that describes the dynamics of fatigue crack propagation for the considered truss in the zone of thermal influence from the weld (Fig. 7).

After analyzing the configuration of the crack propagation graph during cyclic loading (Fig. 9), it is obvious that it approaches the exponential function of the type $y=a^{x}$.

Based on the results of processing the numerical (Table 3) and graphical (Fig. 9) information obtained during the experimental studies, an analytical dependence was proposed to determine the crack length l (mm) during its propagation under the condition of multi-cycle fatigue:

$$l=1,6(1,04^{n\cdot 10^{-4}}-1)+l_0 \,, \qquad (1)$$

where n is the number of loading cycles after fixing the first visually detectable crack; l_0 – the length of the first visually visible crack at the time of its detection.

Analytical calculations were performed to determine the crack length using formula (1). For comparison with experimental values, the results are summarised in Table 4 and Fig. 10.

Table 4

Crack length according to the results of full-scale studies of the physical model of
a welded truss under cyclic loading

Number of cycles, $n \times 10^5$	0	1	2	3	4	5	6	7
Experimental crack length *l, mm*	3,8	4,8	5,6	7,2	9,7	13,5	18,9	26,8
Estimated crack length *l, mm*	3,8	4,6	5,7	7,4	9,9	13,6	19,0	27,1

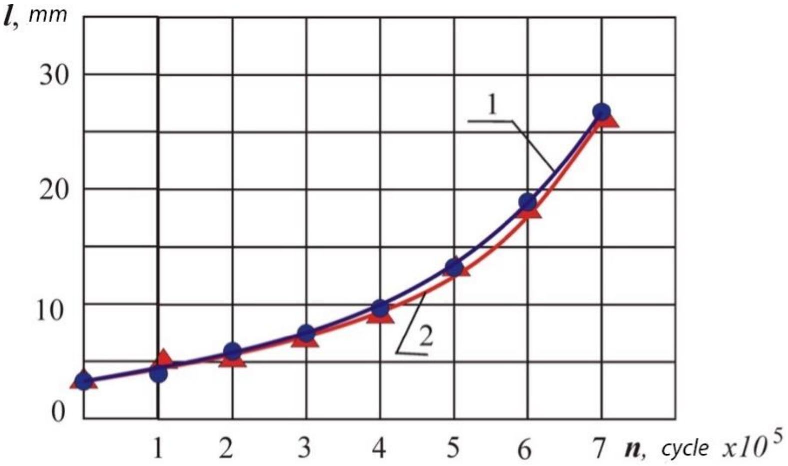


Figure 10. Summary graph of crack propagation during cyclic loading:
1 – according to formula (1), 2 – according to the results of the experiment

It is obvious that the calculated and experimental results are in satisfactory agreement, which indicates the feasibility of using the proposed dependence in engineering practice to predict fatigue damage of this type of truss and prevent its destruction under cyclic loads. Using the similarity constants based on the principles of physical modelling, the results obtained are transferred to assess the behaviour of full-scale trusses of the same configuration under cyclic loads

4. CONCLUSIONS

1. The results of experimental studies revealed the location of the fatigue crack, the duration of the truss operation before the appearance of a visually noticeable crack, and the dynamics of its propagation.

2. An analytical dependence was developed to determine the dynamics of fatigue crack propagation during the operation of a truss under cyclic loads.

3. Based on the results obtained, recommendations for the safe operation of a full-scale farm under cyclic loads were formulated:

– the maximum load in the cycle should not exceed 66.7% of the maximum static load of elastic deformation of the structure;

– for the studied structure, when operated under cyclic loads, a fatigue crack will form in the thermal impact zone in the side assembly on the lower belt;

– the dynamics of fatigue crack propagation after its appearance can be predicted by the proposed analytical dependence.

4. The following options are available to increase the service life of the truss before or after a crack occurs:

- reduce the load in the cycle;
- reinforce the truss assembly at the point of cracking.

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ПОШКОДЖЕННЯ І РУЙНУВАННЯ ЗВАРНОЇ ФЕРМИ З ПАРАЛЕЛЬНИМИ ПОЯСАМИ ПРИ ДІЇ ЦИКЛІЧНИХ НАВАНТАЖЕНЬ

Роман Грицеляк

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Визначено вплив експлуатаційних циклічних навантажень на пошкодження зварних ферм. Згідно з технічним завданням необхідно було виявити місце зародження втомної тріщини і можливість експлуатації зварної ферми з наявною тріщиною до настання граничного стану конструкції* *для прямокутної ферми з розмірами 12000х2400 мм, призначеної для закріплення до вузлів на верхньому поясові опор підіймального крана. Складність таких досліджень полягає у багатофакторному впливові на процес зародження й поширення втомних тріщин у конструктивних елементах зварних ферм і у місцях їх зварних з'єднань. Запропоновано методичний підхід на основі дослідження фізичної моделі ферми, тобто напівнатурним експериментом. Такий підхід використовується для дослідження велико-габаритних конструкцій і дає можливість врахувати багатопараметричний вплив у конструктивних, технологічних та експлуатаційних чинниках, виявити місця зародження початкової втомної тріщини, поширення якої в подальшому зумовить руйнування конструкції. Для досліджень розроблено фізичну модель 600х120 прямокутної зварної ферми з паралельними поясами. Схема її базування й навантаження відповідає умовам для реальної ферми 12000х2400. Фізичну модель 600х120 ферми досліджено при дії статичних та циклічних навантажень на випробувальному комплексі СТМ-100. При дії циклічних навантажень виявлено місце зародження втомної тріщини, визначено швидкість її поширення, знайдено критичну довжину тріщини, за якою ферма руйнується. Розроблено аналітичну залежність для виявлення динаміки поширення втомної тріщини за експлуатації ферми за умов циклічних навантажень. Сформульовано рекомендації щодо безпечної експлуатації зварної ферми за умов циклічних навантажень, її підсилення та ремонту з метою збільшення ресурсу конструкції. Використання результатів роботи в інженерній практиці дасть можливість не допустити аварійного руйнування ферми впродовж її експлуатації.*

Ключові слова: *зварна ферма, міцність і деформівність ферми, циклічні навантаження, руйнування ферми.*

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